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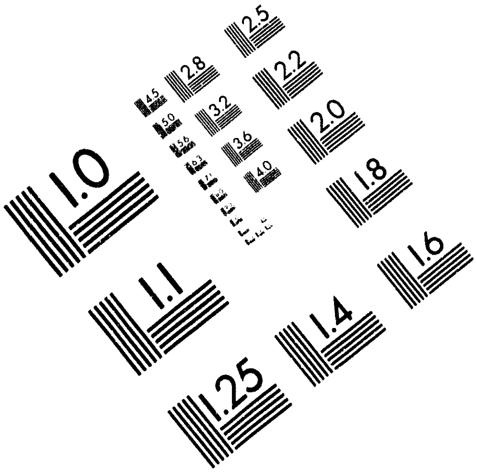

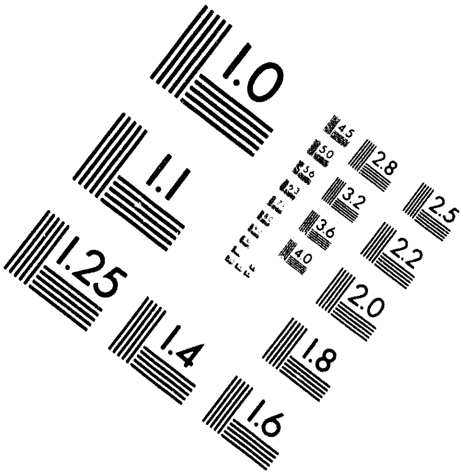

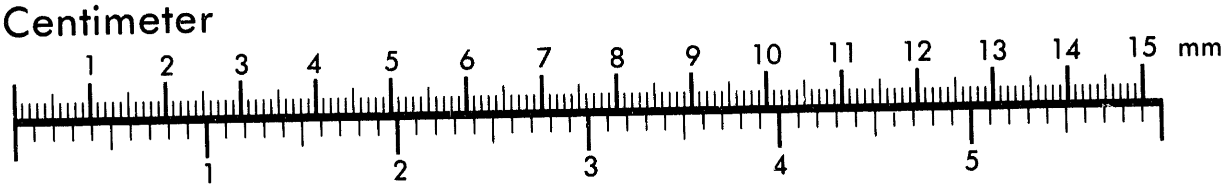

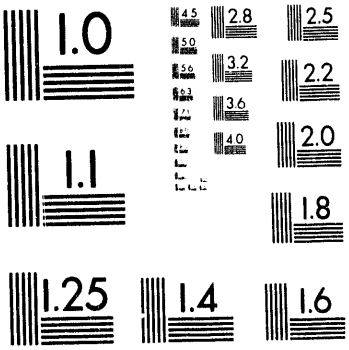

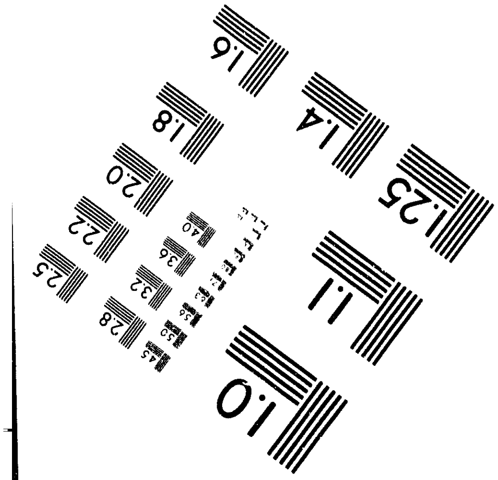

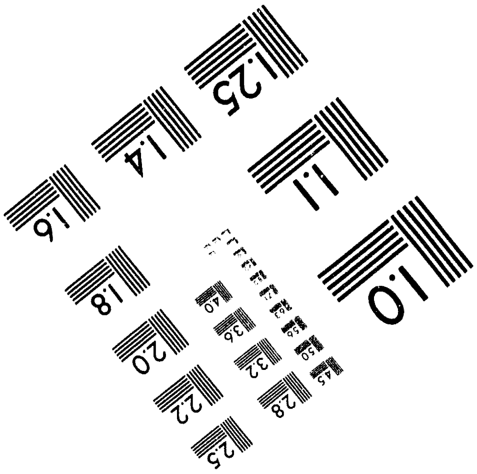

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A CO_2 Laser Polarimeter for Measurement of Plasma Current Profile in Alcator C-Mod

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A multichannel infrared polarimeter system for measurement of the plasma current profile in Alcator C-Mod has been designed, constructed, and tested. The system utilizes a cw CO_2 laser at a wavelength of 10.6 μm. An electro-optic polarization-modulation technique has been used to achieve the high sensitivity required for the measurement. The recent results of the measurements as well as the feasibility of its application on ITER are presented.

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I. INTRODUCTION

A collaboration between Oak Ridge National Laboratory (ORNL) and the MIT Plasma Fusion Center has been undertaken to measure the electron density and plasma current profiles in Alcator C-Mod tokamak by use of a two-color interferometer and an infrared polarimeter. For high density and high plasma current tokamaks, the poloidal magnetic field distribution can be determined by probing the plasma with an array of CO_2 laser beams and measuring the plasma-induced Faraday rotation, θ_f, of the plane of polarization. The rotation angles are proportional to the line integrals of the electron density times the magnetic field component along the probing beam paths. Knowing the electron density distribution from a phase shift (ϕ) measurement with the concomitant interferometer, and using the close relation between the plasma current and the resulting poloidal magnetic field, the integrals can then be inverted to obtain the current density distribution.[1] Because of similarities in the expected phase shift and Faraday rotation between the International Thermonuclear Experimental Reactor (ITER) and the Alcator C-Mod (Table 1), an additional objective of the program is to determine the feasibility of this interferometer/polarimeter system for ITER. The polarimeter is a modification of a previous system developed for CIT.[2] An electro-optic polarization modulator has been developed to achieve the high sensitivity ($\leq 0.01°$) and time resolution

(≤0.1 msec) required for the measurement of the Faraday rotation. The polarimeter has been successfully designed, constructed, and calibrated at ORNL, and has been integrated into the existing two-color interferometer on C-Mod.[3] Detailed analyses and experiments of the previous systems have been reported.[2-4] Only a brief description of the modified system is therefore presented in the following.

II. EXPERIMENT

The two-color heterodyne interferometer consists of ten CO_2 laser (10.6 μm) channels and three HeNe laser (0.6328 μm) channels viewing the plasma vertically with a Michelson geometry. The main components are: a CO_2 laser (MPB Technologies Inc., Model GN 802-20-MES, 20-W, single line), a germanium Bragg cell (Isomet Model 1207 B-6), and a HgCdTe thermoelectrically cooled detector array (Electro-Optical System Inc., Model MCT10TE-010/10ELE). The acoustic optic Bragg cell diffracts approximately 50% of the CO_2 laser power into a reference beam. This cell also introduces a frequency shift (Δf) of 40 MHz in the diffracted beam. The undiffracted probing beam is passed through a ZnSe quarter-wave Fresnel rhomb, a CdTe electro-optic modulator and a mechanical polarization rotator. Emerging from the polarization modulator, the Gaussian beam is expanded to an elliptical beam with a profile of 1×20 cm via cylindrical mirrors in order to view the plasma cross section accessible by the viewing ports. The return beam in the two-pass system is decollimated and is passed through an analyzer. The reference beam is also expanded and is guided to the signal detector array to mix with the probing beam. The detector signals are then filtered, amplified, and fed into digital phase detection circuits to extract the phase shifts between the output of the signal detectors and the reference signal. These phase shifts are proportional to the line-integrated electron densities along the 10 vertical chords.

Figure 1 shows a simplified sketch of the arrangement of the polarimeter. The electro-optic modulator (II-VI Inc. Model EOM5-10.6-0450-C) consists of a ZnSe quarter-wave Fresnel rhomb, and a CdTe crystal of 4×4×50 mm operating with a half-wave voltage of 4.24 kV. Both the probing beam and the reference beam are initially linearly polarized with their electric fields in the x-direction. The ZnSe Fresnel rhomb shown causes the probing beam to be totally reflected internally twice (with an incident angle of 65.57°), thereby changing the probing beam into a circularly polarized wave.[5] The modulator is driven by a 800 KHz oscillator-amplifier system with the electric field applied in the x-direction. The mechanical polarization rotator consists of three mirrors mounted on a rotatable frame such that the polarization of the probing beam changes by twice the angle of the frame rotation. Emerging from the plasma, the probing beam is passed through an analyzer. The analyzer is oriented with its axis in the x-direction, so that only the x-component of the probing beam is mixed with the reference beam at the detector. The output of the signal detector, V_s, can be expressed by the following relation:

$$
\begin{aligned}
V_s &= \{ (RP_p)^{1/2} [\mathrm{Cos}(\theta)\ \mathrm{Cos}(\omega_p t - \phi - \phi_m) - \mathrm{Sin}(\theta)\ \mathrm{Sin}(\omega_p t - \phi)] \\
&\quad + (RP_r)^{1/2}\ \mathrm{Cos}(\omega_r t) \}^2 \\
&= -\ RP_p J_1(\theta_m)\ \mathrm{Sin}(2\theta)\ \mathrm{Sin}(\omega_m t) \\
&\quad + R(P_p P_r)^{1/2} [\mathrm{Cos}(\theta)\mathrm{Cos}(\Delta\omega t + \phi + \phi_m) + \mathrm{Sin}(\theta)\mathrm{Sin}(\Delta\omega t + \phi)] \\
&\quad + \text{terms of dc and other frequencies}\ , \qquad (1)
\end{aligned}
$$

where R is the responsivity of the detector; θ is the sum of the polarization rotation angle due to the mechanical rotator, θ_b, and the Faraday rotation in plasma, θ_f; ω_m is the modulation frequency; ω_p and ω_r are the frequencies of the probing and reference beam respectively; $\Delta\omega = \omega_p - \omega_r$; $J_1(\theta_m)$ is the Bessel function of the first kind with order 1; and P_p and P_r are the power of the probing and reference beam at the detector respectively. The modulation of the phase shift between X-component and Y-component of the electric field, ϕ_m, is sinusoidal and can be written as

$$\phi_m = \theta_m\ \mathrm{Sin}(\omega_m t) \qquad (2)$$

where θ_m is the amplitude of the modulation angle in degrees and is related to the modulation voltage, V_m, and the half wave voltage of the CdTe crystal, V_π, by

$$\theta_m = 180\ V_m/V_\pi \qquad (3)$$

For small θ_f and by setting the mechanical polarization rotator at the 45° position ($\theta_b = 90°$), Eq. (1) becomes

$$V_s = RP_pJ_1(\theta_m)\ \mathrm{Sin}(2\theta_f)\ \mathrm{Sin}(\omega_m t)$$
$$+ R\ (P_pP_r)^{1/2}\ \mathrm{Cos}(\theta_f)\ \mathrm{Sin}(\Delta\omega t + \phi)$$
$$+ \text{terms of dc and other frequencies} \qquad (4)$$

The phase shift, ϕ, is derived from the second term of Eq. (4) using the concomitant interferometer. The amplitude of this term is proportional to the laser power times Cos(θ_f) and is independent of the modulation. For angles $\theta_f \leq 5°$, the interferometer signal varies less than 0.4%; therefore, its effect on the phase measurement is negligible. The detector signal at the modulation frequency is synchronously detected by a lock-in amplifier. The output voltage of the amplifier is then

$$V_{out} = ARP_pJ_1(\theta_m)\ \mathrm{Sin}(2\theta_f) \qquad (5)$$

where A is the voltage gain of the amplifier. The values of the individual components of Eq. (5) may be lumped into a single calibration constant, V_o, so that Eq. (5) becomes

$$V_{out} = V_o\ \mathrm{Sin}(2\theta_f) \qquad (6)$$

where $V_o = ARP_pJ_1(\theta_m)$. The value of V_o can be obtained by setting the mechanical polarization rotator at a calibration angle, θ_c, of a few degrees ($\leq 2°$) away from its original 45° position and measuring a calibration voltage, V_c, at the output of the lock-in amplifier before the beginning of the plasma discharge. The voltage V_o is related to V_c and θ_c by

$$V_o = V_c\ /\ \mathrm{Sin}(4\theta_c) \qquad (7)$$

The V_o as determined by this technique calibrates the polarimeter in a manner that does not require the absolute knowledge of the laser power, the detector responsivity, the modulation angle, or the gain of the amplifier. For small rotation angles, $(\theta_f + 2\theta_c) \leq 5°$, V_{out} is a direct measure of θ_f, since $\mathrm{Sin}[2(\theta_f + 2\theta_c)] \cong 2\ (\theta_f + 2\theta_c)$, and Eqs. (6) and (7) are reduced to the form

$$\theta_f = 2\theta_c\ (V_{out}/V_c - 1) \tag{8}$$

The outputs of the lock-in amplifiers are digitized for computer storage and processing. The values of the Faraday rotation angles along the 10 vertical chords are calculated according to Eq. (8).

A test bench of the polarimeter system was set up at ORNL to determine the performance characteristics of the system. Since the signal at the modulation frequency is only proportional to the power of the probing beam, the first experiment was performed with the reference beam blocked. Figure 2(a) shows the frequency spectrum of the modulated signal at 800 kHz with $\theta_b = 45°$. It can be seen in this figure that the signal-to-noise ratio of the modulated signal is approximately 20 dB. The high signal-to-noise ratio was achieved with only 1 W of CO_2 laser power and without any beam focusing. The second experiment was performed with reference beam and $\theta_b = 0°$. Figure 2(b) shows the frequency spectrum of the heterodyne beat signal at 40 MHz and the sideband frequencies of ±800 kHz. The signal-to-noise ratio of the sidebands is also approximately 20 dB. Finally, the calibration experiment was carried out with the mechanical polarization rotator oriented at 46° position. Under this condition, a Faraday rotation of 2° was simulated. The output voltage of the lock-in amplifier was measured to be about 350 mV. With both beams blocked, an output voltage in the range of 1-2 mV was observed, thus a polarimeter sensitivity better than 0.01° was achieved. It is of interest to note that the sensitivity can be further enhanced by using a technique of two lock-in amplifiers connected in series. The first amplifier is synchronized at 40 MHz, and its output is fed into the second lock-in amplifier which is synchronized to the modulation frequency of 800 kHz. The only draw-back of this technique is that a reference signal detector is needed for the density measurement. The polarimeter has been added in the existing two-color interferometer system on Alcator C-Mod. The interferometer/polarimeter system has been successfully aligned and the measurements are under way.

ACKNOWLEDGMENTS

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TABLE I. Design considerations for two-color interferometer / polarimeter system

	C-MOD (Double Pass)	ITER (Single Pass)
Wavelength (microns)	10.6	10.6
Major radius (M)	0.65	7.75
Minor radius (M)	0.2	2.75
Central density ($10^{20}/m^3$)	10	1.78
Plasma current (MA)	3	25
Toroidal field (T)	9	6
Faraday rotation (deg)	1.4	1.4
Ellipticity	$7.6 \cdot 10^{-6}$	$1.3 \cdot 10^{-5}$
Phase shift (fringes)	2.5	2.7

Figure Captions

Fig. 1. Illustration of the electro-optic polarization-modulation technique used in the CO_2 laser polarimeter on Alcator C-Mod.

Fig. 2. Frequency spectra of (a) the modulated signal at 800 kHz with $\theta_b = 45°$, and (b) the heterodyne beat signal at 40 MHz and the sideband frequencies of ±800 kHz with $\theta_b = 0°$.

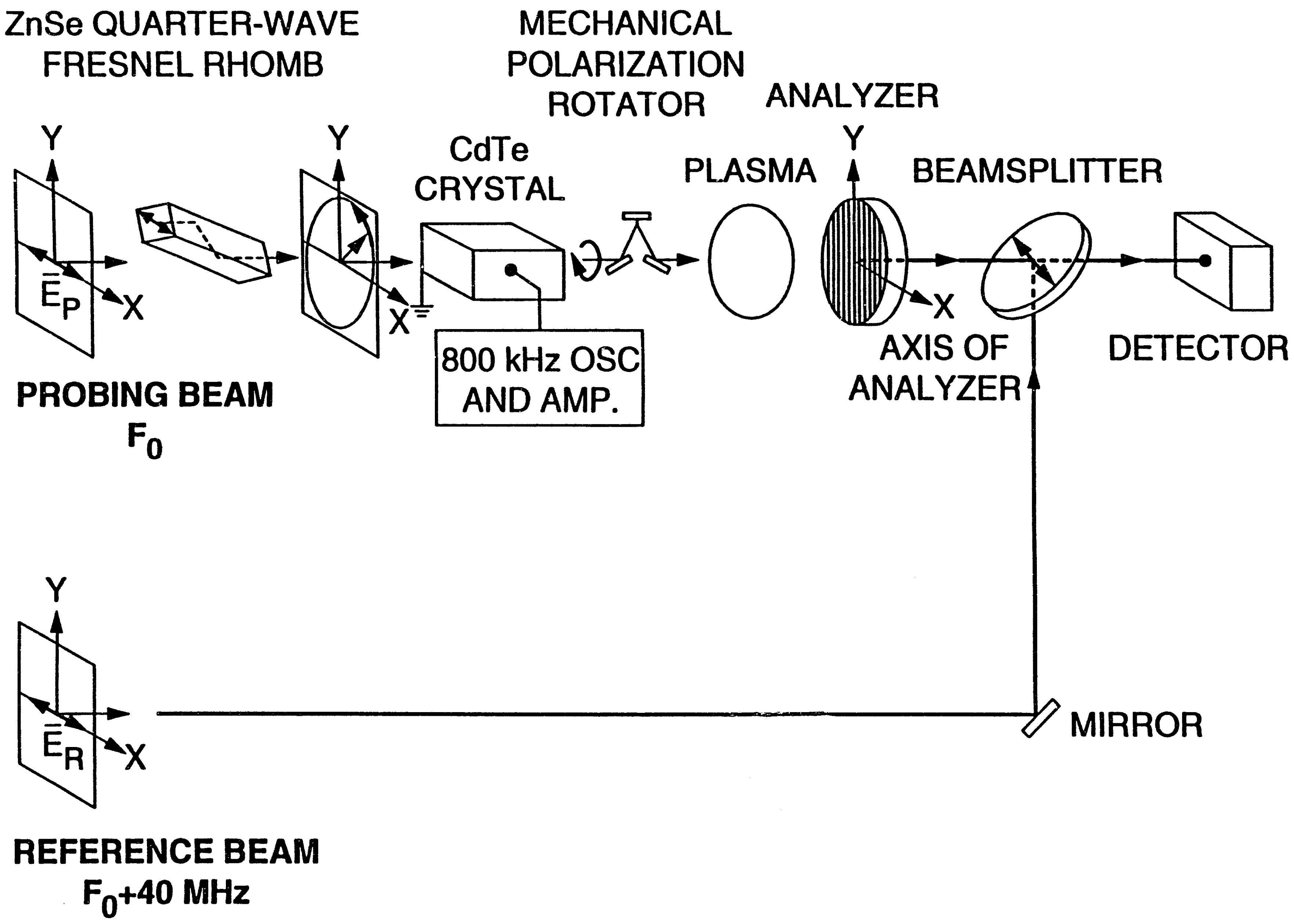
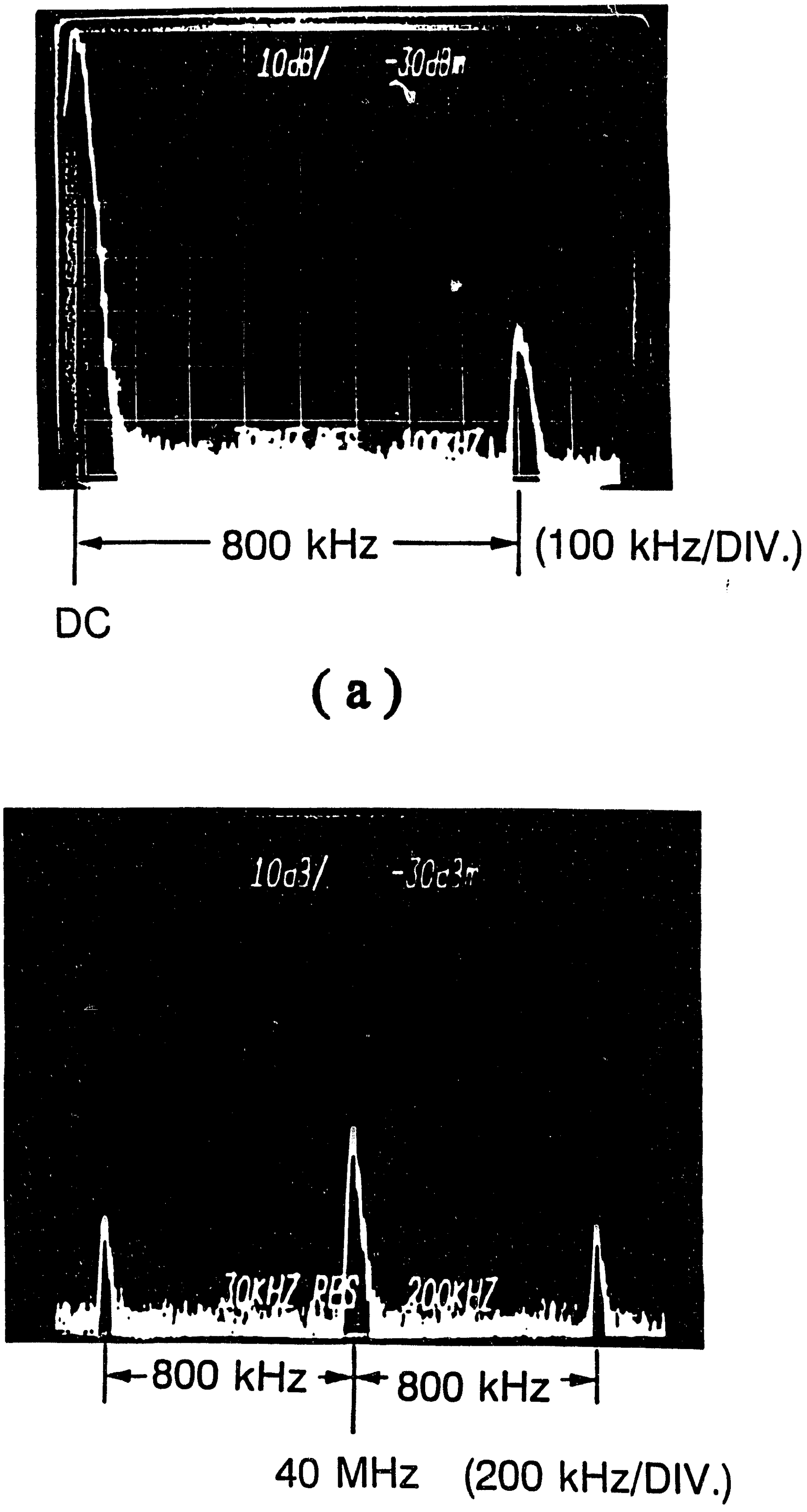

ZnSe QUARTER-WAVE FRESNEL RHOMB
MECHANICAL POLARIZATION ROTATOR
ANALYZER
Y
Y
CdTe CRYSTAL
PLASMA
Y
BEAMSPLITTER
$\bar{E}_P$
X
X
X
800 kHz OSC AND AMP.
AXIS OF ANALYZER
DETECTOR
PROBING BEAM
F_0
Y
$\bar{E}_R$
X
MIRROR
REFERENCE BEAM
F_0+40 MHz

Fig. 1


10dB/
-30dBm
800 kHz
(100 kHz/DIV.)
DC
10dB/
-30dBm
30KHZ RES
200KHZ
800 kHz
800 kHz
40 MHz
(200 kHz/DIV.)

(a)

(b)

Fig. 2

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